

## EARLY X-RAY AND OPTICAL AFTERGLOW OF GRAVITATIONAL WAVE BURSTS FROM MERGERS OF BINARY NEUTRON STARS

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## ABSTRACT

Double neutron star mergers are strong sources of gravitational waves. The upcoming advanced gravitational wave detectors are expected to make the first detection of gravitational wave bursts (GWBs) associated with these sources. Proposed electromagnetic counterparts of a GWB include a short GRB, an optical macronova, and a long-lasting radio afterglow. Here we suggest that at least some GWBs could be followed by an early afterglow lasting for thousands of seconds, if the post-merger product is a highly magnetized, rapidly rotating, massive neutron star rather than a black hole. This afterglow is powered by dissipation of a proto-magnetar wind. The X-ray flux is estimated to be as bright as  $(10^{-8} - 10^{-7}) \text{ erg s}^{-1} \text{ cm}^{-2}$ . The optical flux is subject to large uncertainties but could be as bright as 17th magnitude in R-band. We provide observational hints of such a scenario, and discuss the challenge and strategy to detect these signals.

## 1. INTRODUCTION

Mergers of neutron-star/neutron-star (NS-NS) binaries are strong sources of gravitational waves (e.g. Kramer et al. 2006). The upcoming advanced gravitational wave detectors such as Advanced LIGO (Abbott et al. 2009) and Advanced VIRGO (Acernese et al. 2008) are expected to expand the detection horizon to a few hundred Mpc for NS-NS mergers as early as 2015. Theoretical motivation (Eichler et al. 1989; Narayan et al. 1992; Rosswog et al. 2012) and observational progress (e.g. Gehrels et al. 2005; Barthelmy et al. 2005; Berger et al. 2005) suggest that at least some short gamma-ray bursts (SGRBs) may be related to NS-NS mergers. This hypothesis can be proved when both a SGRB and a gravitational wave burst (GWB) are detected in coincidence with each other in trigger time and direction. On the other hand, observations of SGRBs suggest that at least some of them are collimated (e.g. Burrows et al. 2006; De Pasquale et al. 2010). Since the strength of the gravitational wave signals does not sensitively depend on the orientation of the NS-NS merger orbital plane with respect to the line of sight, most GWBs would not be associated with SGRBs even if the SGRB-GWB association is established. Searching for electromagnetic counterparts of SGRB-less GWBs is essential to confirm the astrophysical origin of the GWBs, and to advance our understanding of the compact star merger physics. In the literature, an optical “macronova” (Li & Paczyński 1998; Kulkarni 2005; Metzger et al. 2010) due to decay of the ejecta launched during the merger<sup>4</sup> and a long-lasting radio afterglow due to interaction between the ejecta and the ambient medium (Nakar & Piran 2011; Metzger & Berger 2012; Piran et al. 2012) have been predicted. Both are

challenging to detect (Metzger & Berger 2012). Here we suggest another possible electromagnetic counterpart of GWBs. We argue that if the post-merger product is a short-lived massive neutron star rather than a black hole, a SGRB-less GWB could be followed by an early X-ray and optical afterglow extending for thousands of seconds. We provide observational hints of such a possibility in §2. In §3, we estimate the duration and brightness of the X-ray and optical afterglows, and discuss their detectability. A brief summary is given in §4.

## 2. MASSIVE NEUTRON STAR AS THE POST-MERGER OBJECT

There are two lines of reasoning to suspect that NS-NS mergers can produce a massive NS rather than a black hole, which may survive for an extended period of time of the observational interest. The first is along the line of the observations of NSs and NS-NS binaries in the Galaxy (e.g. Lattimer (2012) for a review). A secure lower limit of the maximum NS mass is set by PSR J1614-2230 (in a NS-WD binary) to  $1.97 \pm 0.04 M_{\odot}$  through a precise measurement of the Shapiro delay (Demorest et al. 2010). NSs with possibly even higher masses, albeit with large uncertainties, are also suggested. For example, the NS candidate in the X-ray binary 4U 1700-377 has a mass  $2.44 \pm 0.27 M_{\odot}$  (Rawls et al. 2011), and the NS in the NS-WD binary PSR B1516+02B has a mass  $2.08 \pm 0.19 M_{\odot}$  (Freire et al. 2008). A stiff equation of state (EOS) of neutron matter is demanded by the data. Although current data do not allow to differentiate among various stiff EOS models, most of these stiff-EOS NS models predict a maximum NS mass close to or higher than  $2.5 M_{\odot}$  for a non-rotating NS (Lattimer 2012). For rapidly spinning NSs which are likely relevant for the post-merger products, the maximum mass can be even higher due to a centrifugal support. On the other hand, the observations of the Galactic NS-NS systems suggest that the NS mass in these systems peak at  $1.35 M_{\odot}$ , and the sum of the two NS masses for a significant fraction of the population is around  $2.6 M_{\odot}$  (Lattimer 2012). Numerical simulations suggest that NS-NS mergers typically eject several percent solar masses (Rosswog et al. 2012). As a re-

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<sup>4</sup> Kyutoku et al. (2012) conjectured that a tip of such an ejecta can reach relativistic speed and give broad-band afterglow in a wide solid angle.

sult, the post-merger products of at least a fraction (e.g.  $f_{\text{NS}} \sim 0.5$ ) of NS-NS merger events should have a total mass below the maximum NS mass of a rapidly spinning NS. This NS would not collapse until losing a significant amount of angular momentum within the characteristic spin-down time scale. Such a possibility was suggested by Dai et al. (2006) and Gao & Fan (2006) to interpret X-ray flares and plateaus following SGRBs, and is now strengthened by additional data.

The second line of reasoning is based on the observations of the SGRB X-ray afterglows. The most direct evidence of a spinning-down object at the SGRB central engine is in GRB 090515 detected by Swift (Rowlinson et al. 2010). After a short prompt emission phase lasting for  $T_{90} = 0.036 \pm 0.016$  s, the burst showed an X-ray plateau that lasted for  $\sim 240$  s, after which the flux declines rapidly, and became undetectable by XRT at  $\sim 500$  s after the trigger (Rowlinson et al. 2010). Such a steady plateau with rapid decline would be a signature of a magnetar at the central engine (Zhang & Mészáros 2001; Troja et al. 2007). Even though no redshift measurement was made for this burst, an analysis suggests that the presumed heavy NS has parameters consistent with a magnetar for a reasonable redshift range (Rowlinson et al. 2010). A later systematic analysis of Swift SGRB X-ray lightcurves suggests that a significant fraction of SGRBs have evidence of an X-ray plateau followed by a steep drop in flux, which is consistent with a magnetar central engine (Rowlinson & O’Brien 2012). If SGRBs are associated with NS-NS mergers, it is likely that a millisecond magnetar survived in these SGRBs.

Another indirect piece of evidence is X-ray flares following some SGRBs (Barthelmy et al. 2005). A possible interpretation is the magnetic activity of a differentially rotating massive NS after a NS-NS merger (Dai et al. 2006). If the magnetic field strength of this post-merger massive NS is not too high (similar to that of normal pulsars), the magnetic activity of the NS has the right time scale and luminosity to account for X-ray flares.

### 3. EARLY X-RAY AND OPTICAL AFTERGLOW OF NS-NS MERGER-INDUCED GWBS

At least some SGRBs are collimated (Burrows et al. 2006; De Pasquale et al. 2010). For the standard X-ray afterglow component (that originates from the external shock of the SGRB jet), the afterglow jet opening angle is believed to be comparable to the prompt emission jet opening angle, so that a GWB without a SGRB association would have a very faint “orphan” afterglow peaking at a time when the jet is decelerated enough so that the  $1/\Gamma$  cone enters line-of-sight. The prospects of detecting such a SGRB orphan afterglow are poor. Here we suggest that the afterglow powered by a rapidly spinning massive NS has a much wider solid angle than the solid angle of the SGRB jet, so that *SGRB-less GWBs can also have a bright afterglow from a dissipating proto-magnetar wind with a large solid angle*. At the base of the central engine (light cylinder), the wind launched from the millisecond magnetar is essentially isotropic. Numerical simulations suggest that this proto-magnetar wind from a NS-NS merger progenitor would be collimated by the ejecta launched during the merger process, but with a much larger angle,  $30^\circ - 40^\circ$ , than the case of a massive-star core-collapse progenitor (Bucciantini et al. 2012). This

is much larger than the jet opening angle inferred from the afterglow modeling of some SGRBs (Burrows et al. 2006; De Pasquale et al. 2010). A wider solid angle of proto-magnetar wind than the GRB jet angle was also inferred from an analysis of the magnetar engine candidates for long GRBs (Lyons et al. 2010).

In the following, we adopt the *ansatz* that some NS-NS mergers produce a massive magnetar. The proto-magnetar wind is essentially isotropic at the base, with a wide solid angle  $\theta_{w,1} \sim 40^\circ$  for a free wind (with a beaming factor  $f_{b,w,1} = \Delta\Omega_{w,1}/4\pi \sim 0.2$ ) and an even larger solid angle  $\Delta\Omega_{w,2}$  in the equatorial direction for a confined wind that pushes the heavy ejecta launched during the merger phase (with a beaming factor  $f_{b,w,2} = \Delta\Omega_{w,2}/4\pi \sim 0.8$ , so that the total beaming factor is  $f_{b,w} = f_{b,w,1} + f_{b,w,2} \sim 1$ ). This hypothesis applies regardless of whether the GWB is associated with a SGRB. If there is a GWB/SGRB association, we expect that SGRB jets have a much smaller solid angle. For example, if the typical SGRB jet opening angle is  $\theta_j \sim 10^\circ$ , one has the jet beaming factor  $f_{b,j} = \Delta\Omega_j/4\pi \sim 0.015$ , so that  $\Delta\Omega_j \ll \Delta\Omega_{w,1} < \Delta\Omega_{w,2}$ .

The NS-NS merger event rate is very uncertain. The rate inferred from the Galactic NS-NS systems has a wide range  $2 - 2 \times 10^4 \text{ Gpc}^{-3} \text{ yr}^{-1}$  (Phinney 1991; Kalogera et al. 2004; Abadie et al. 2010). This is consistent with the upper limit  $2 \times 10^5 \text{ Gpc}^{-3} \text{ yr}^{-1}$  set by the current non-detection with the last LIGO and VIRGO run (Abbott et al. 2009). Within the advanced LIGO horizon  $\sim 300$  Mpc, the NS-NS merger rate (and therefore GWB rate) would be  $R_{\text{GWB}} \sim (0.2 - 2000) \text{ yr}^{-1}$ . Among these,  $R_{\text{GWB-ag}} \sim (0.1 - 1000)(f_{\text{NS}}/0.5)(f_{b,w}) \text{ yr}^{-1}$  would have strong afterglow emission associated with the proto-magnetar wind, most of which would not have a SGRB association, since the line of sight is outside the SGRB cone even if there is a SGRB/GWB association.

After the merger, the proto-NS is initially very hot and cools via neutrino emission. After about 10 seconds, the NS is cooled enough so that a Poynting-flux-dominated outflow can be launched (Usov 1992; Metzger et al. 2011). It will be spun down by magnetic dipole radiation and by the torque of a strong electron-positron pair wind flowing out from the magnetosphere. Since before the merger the two NSs are in the Keplerian orbits, the post-merger product should be near the break-up limit. We take  $P_0 = 1 \text{ ms}$   $P_{0,-3}$  as a typical value of the initial spin period of the proto-magnetar. An uncertain parameter is the polar-cap magnetic field of the dipole magnetic field component,  $B_p$ , which depends on whether the  $\alpha - \Omega$  dynamo is efficiently operating, and on the magnetic field strength of the parent NSs if the dynamo mechanism is not efficient. Given nearly the same amount of the total rotation energy  $E_{\text{rot}} = (1/2)I\Omega_0^2 \sim 2 \times 10^{52} \text{ erg}$  ( $\Omega_0 = 2\pi/P$ ), the luminosity, and hence, the afterglow flux critically depend on  $B_p$ . As a rough estimate, we apply the dipole spin-down formula. Correcting for the beaming factor  $f_w$  and the efficiency factor  $\eta_x$  to convert the spin down luminosity to the observed X-ray luminosity in the detector band, one gets

$$F_x = \frac{\eta_x L_{sd}}{4\pi f_{b,w} D_L^2} \simeq 2 \times 10^{-8} \text{ erg s}^{-1} \text{ cm}^{-2}$$

$$\times \eta_{x,-2} f_{b,w}^{-1} \left( \frac{D_L}{300 \text{ Mpc}} \right)^{-2} I_{45} P_{0,3}^{-2} T_{sd,3}^{-1}, \quad (1)$$

where  $L_{sd} = I \Omega_0^2 / (2 T_{sd})$  is the characteristic spindown luminosity, and

$$T_{sd} \simeq 2 \times 10^3 \text{ s } I_{45} B_{p,15}^{-2} P_{0,-3}^2 R_6^{-6} \quad (2)$$

is the characteristic spindown time scale. Here  $I = 10^{45} I_{45}$  is the moment of inertia (typical value  $I_{45} = 1.5$  for a massive NS),  $R = 10^6 R_6$  is the radius of the NS, and the convention  $Q_x = Q/10^x$  has been adopted. Here we have assumed that a good fraction ( $\eta_x \sim 0.01$ ) of spin down energy is released in the X-ray band. This is based on the following two considerations: First, some SGRBs indeed have a bright X-ray plateau that is likely due to the magnetar spindown origin (Rowlinson et al. 2010; Rowlinson & O'Brien 2012), which suggests that the main energy channel of releasing the magnetic dissipation energy is in the X-ray band. Second, a rough theoretical estimate shows that the typical energy band of a dissipating magnetized wind with a photon luminosity  $L_\gamma \sim 10^{49} \text{ erg s}^{-1}$  could be in X-rays.

We consider two mechanisms to dissipate the magnetar wind energy to radiation. (1) In the free wind zone with solid angle  $\Delta\Omega_{w,1}$ , one may consider a magnetized wind with a luminosity  $L_w$  and magnetization parameter  $\sigma(R)$  dissipated at a radius  $R$  from the central engine. Assuming that the magnetic energy is abruptly converted to the internal energy of power-law distributed electrons (such as in the scenario of the ICMART model), one can generally estimate the typical synchrotron energy as (Zhang & Yan 2011)  $E_p \simeq 80 \text{ keV } L_{\gamma,48}^{1/2} R_{15}^{-1} \eta_{x,-2}^{3/2} \sigma_0^2$ . A cooled-down proto-magnetar typically has  $\sigma_0 \sim 10^9$  at the central engine (Metzger et al. 2011). A magnetized flow can be quickly accelerated to  $\Gamma \sim \sigma_0^{1/3} \sim 10^3$  at  $R_0 \sim 10^7 \text{ cm}$ , where  $\sigma \sim \sigma_0^{2/3} \sim 10^6$  (Komissarov et al. 2009). After this phase, the flow may still accelerate as  $\Gamma \propto R^{1/3}$ , with  $\sigma$  falling as  $\propto R^{-1/3}$  (Drenkhahn & Spruit 2002). At  $R \sim 10^{15} \text{ cm}$ , one has  $\sigma \sim 2 \times 10^3$ , so that  $E_p \sim 3.7 \text{ keV}$ , which is in the X-ray band. (2) One can also consider the confined magnetar wind zone with solid angle  $\Delta\Omega_{w,2}$  where the magnetar wind is expanding into a heavy ejecta launched during the merger process<sup>5</sup>. The magnetic energy may be rapidly discharged upon interaction between the wind and the ejecta, which occurs at a radius  $R \sim vt_{\text{delay}} = 3 \times 10^{10} \text{ cm} (v/0.1c) t_{\text{delay},1}$ , where  $v \sim 0.1c$  is the speed of ejecta, and  $t_{\text{delay}} \sim 10 \text{ s}$  is the delay time between the merger and the launch of a high- $\sigma$  magnetar wind. The Thomson optical depth for a photon to pass through the ejecta shell is  $\tau_{th} \sim \sigma_T M_{ej} / (4\pi R^2 m_p) \sim 7 \times 10^8 (M_{ej}/(0.01 M_\odot)) \gg 1$ . So the spectrum of the dissipated wind is thermal-like. One can estimate the typical energy  $\sim k(L_w/4\pi R^2 \sigma)^{1/4} \sim 5 \text{ keV } L_{w,49}^{1/4} (R/(3 \times 10^{10} \text{ cm}))^{-1/2}$ , which is also in the X-ray band.

One can see that the X-ray band flux of the early afterglow (Eq.1) is very high, well above the sensitivity

threshold of Swift XRT (Moretti et al. 2007)

$$F_{x,th} = 6 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2} T_{\text{obs},2}^{-1}, \quad (3)$$

where  $T_{\text{obs}}$  is the observation time. The light curve is expected to be flat (a plateau) lasting for a duration  $T_{sd}$  followed by a  $t^{-2}$  decay. However, since the NS spins down quickly in the  $t^{-2}$  regime, it is likely that it would lose centrifugal support and collapse to a black hole shortly after the end of the plateau. In this case, essentially all the materials collapse into the BH, without substantial accretion afterwards. The light curve then shows a very sharp drop in flux at the end of the plateau, similar to what is seen in GRB 090515 (Rowlinson et al. 2010).

The challenge to detect such a bright X-ray afterglow following a GWB is its short duration (Eq.2) and the large error box of a GWB trigger. This requires a Swift-like space detector for quick slew, but the error box of the GWB trigger, typically a few tens to a hundred square degrees (Abadie et al. 2012), is much larger than the XRT field of view (0.16 square degree). How to efficiently search for the bright X-ray source within  $T_{sd}$  in such a large sky area is challenging. Even though some strategies using Swift have been proposed (Kanner et al. 2012), the current searches for the GWB afterglow typically happen about half-day after the GWB trigger (Evans et al. 2012). The problem can be alleviated if  $B_p$  of the proto-NS is weaker. For example, even for a typical pulsar field  $B_p \sim 10^{12} \text{ G}$  (Dai & Lu 1998; Dai et al. 2006), the X-ray luminosity can be still as high as  $5 \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}$  for detection, while the duration of the plateau extends to  $T_{sd} \sim 2 \times 10^7 \text{ s}$ . This would give enough time to search for the X-ray afterglow. However, strong magnetic fields are likely generated during the merger events (Price & Rosswog 2006). Very likely one has to face the large-error-box, short-duration problem. An ideal strategy to observe this early afterglow is to design a large field-of-view imaging X-ray telescope, preferably with fast-slewing capability. Such a telescope, even with a moderate sensitivity, can catch the bright early X-ray afterglows of SGRB-less GWBs. The new mission concept ISS-Lobster (Gehrels et al. 2012) invokes an X-ray wide-field imager with a 0.5-sr field of view that covers  $\sim 50\%$  of the sky every 3 hours, which is ideal to detect this bright X-ray afterglow.

The optical flux of the proto-magnetar wind is subject to uncertainties. In the free wind zone (solid angle  $\Delta\Omega_{w,1}$ ), the emission spectral shape is synchrotron. If one has the standard  $F_\nu \propto \nu^{1/3}$  synchrotron spectrum below  $E_p$ , the specific X-ray flux at 1 keV  $F_\nu(X) \sim 4 \text{ mJy}$  would correspond to a R-band magnitude 17. This would be an optimistic estimate of the optical brightness. For the confined wind zone (solid angle  $\Delta\Omega_{w,2}$ ), the spectrum of a dissipating wind is quasi-thermal, and the optical flux is greatly suppressed. Indeed, no bright optical emission was detected during the plateau phase of GRB 090515 (Rowlinson et al. 2010), suggesting that the optical emission of a dissipative proto-magnetar wind is suppressed. Nonetheless, the interaction between the magnetar wind and the ejecta in the confined wind zone can give very interesting radiation signatures in the optical band (H. Gao et al. 2013, in preparation). Wide-field optical telescopes are essential to search for such optical GWB afterglows in the large GWB error box.

<sup>5</sup> I thank Xue-Feng Wu for pointing out this possibility.

The gravitational wave signals from these GWBs have an interesting signature: after the standard chirp signal during the in-spiral and merger phases (Flanagan & Hughes 1998; Kobayashi & Mészáros 2003), there should be an extended GW emission episode afterwards due to a secular bar-mode instability of the newly formed proto-magnetar (Corsi & Mészáros 2009). The signature is in the advanced LIGO frequency band, and can in principle be detected. Jointly detecting such a GW signal along with the X-ray afterglow would give an unambiguous identification of the proto-magnetar nature of the central engine.

Some SGRBs are followed by an extended emission, which sometimes can be very bright (e.g. Gehrels et al. 2006). It is unclear whether the extended emission shares the same solid angle with the short hard spikes. If it has a wider solid angle than the short hard spike emission, as expected in the magnetar engine scenario (e.g. Metzger et al. 2008), then such a bright extended emission (lasting  $\sim 100$  s) can be also associated with SGRB-less GWBs. This emission is brighter than the X-ray afterglow emission discussed above, and can be readily detected by wide-field imagers such as ISS-Lobster.

#### 4. SUMMARY

We have proposed another electromagnetic counterpart of GWBs from NS-NS mergers. It applies to the cases when the two NSs are not very massive (as observed in Galactic double NS systems), so that the post-merger product has a mass below the maximum mass of a rapidly spinning NS. We show that such a scenario is plausible in view of the observations of Galactic NSs, NS-NS systems, and SGRB afterglows. The proto-magnetar would eject a wide-beam wind, whose dissipation would power an X-ray afterglow as bright as  $\sim (10^{-8} - 10^{-7}) \text{ erg s}^{-1} \text{ cm}^{-2}$ . The duration is typically  $10^3 - 10^4$  s, depending on the strength of the dipolar magnetic fields. It is challenging to detect the X-ray afterglow with the current facilities such as Swift, but a wide-field X-ray imager (such as ISS-Lobster) would be ideal to catch this bright X-ray signal. The optical afterglow flux is subject to large uncertainties, but could be as bright as 17th magnitude in R band. Prompt, deep optical follow-up observations of GWBs are desirable. The detection of these signals would confirm the astrophysical origin of GWBs, and shed light into the physics of NS-NS mergers and the NS equation of state.

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